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Michel Faure,1 Wei Lin,2,3 Patrick Monie 4 and Olivier Bruguier5

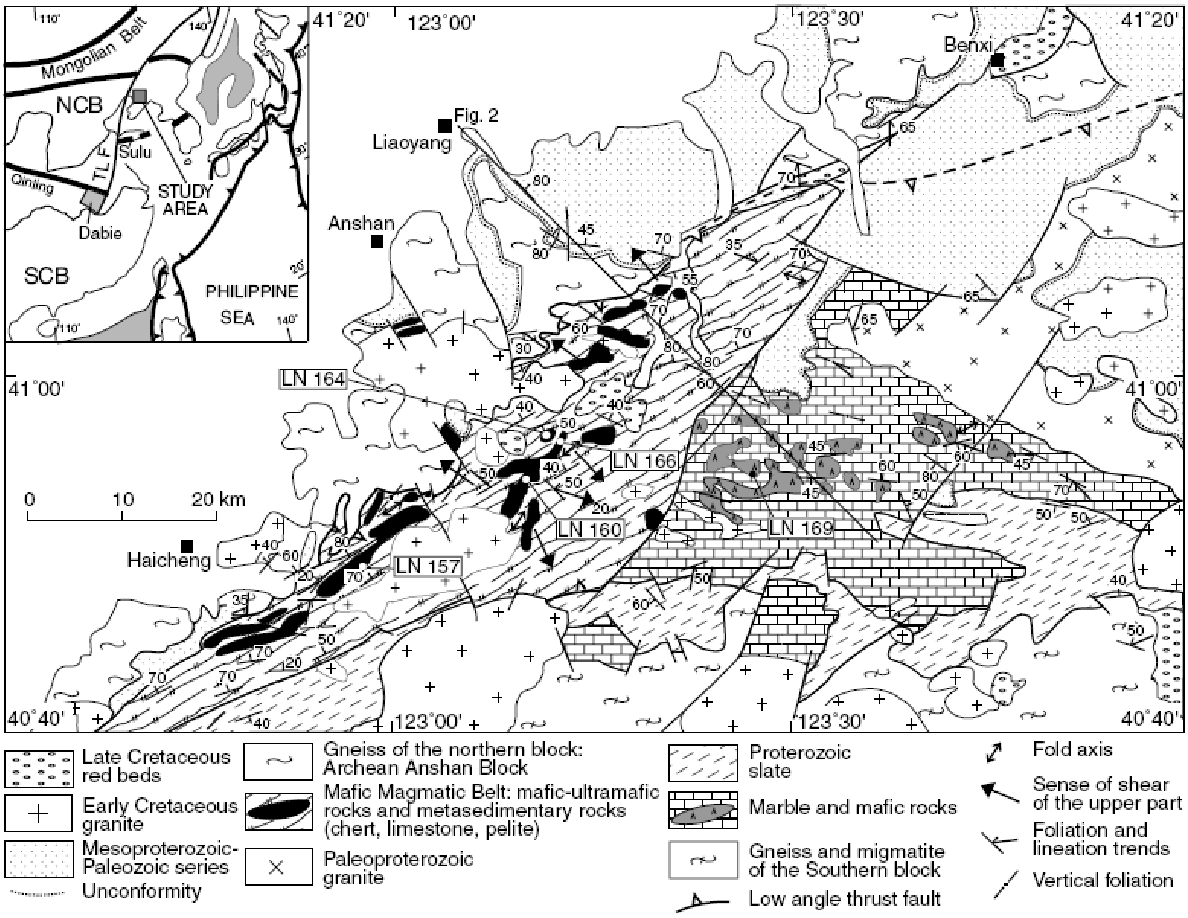
1 - ISTO, UMR CNRS 6113, Batiment Geosciences, Orleans Universite d'Orleans, 45067 Orleans Cedex 2, France;
2 - Institute of Geology and Geophysics, LTE, Chinese Academy of Sciences PO Box 9525 Beijing, 100029, China;
3- Department of Earth and Planetary Sciences, Graduate School of Science, Nagoya University, Japan;
4- Laboratoire Dynamique de la Lithosphe`re, UMR CNRS 5573, Universite de Montpellier 2, 34095 Montpellier Cedex 5, France;
5 - Service Commun ICP-MS, cc 56, ISTEEM, Universite de Montpellier 2, 34095 Montpellier Cedex 5, France

ABSTRACT
In the north-eastern part of the North China Block, a mafic magmatic belt consisting of mafic–ultramafic rocks and marine sedimentary rocks crops out between the northern Archean Anshan Block and a southern Palaeoproterozoic Block. 40Ar ⁄ 39Ar amphibole ages around 1.9 Ga from gabbros, and trace element analyses of gabbros, pyroxenite and shale show that these rocks formed along a Palaeoproterozoic active continental margin. The mafic magmatic belt is interpreted as an arc developed above a south-directed subduction zone, which was subsequently overthrust to the north upon the Anshan Archean Block. This study provides a new example agreeing with increasing evidence supporting plate mobility and thrust tectonics during the Palaeoproterozoic. These new insights must be considered with regard to the formation of the North China Block by magmatic accretion and tectonic collision.

Introduction
Since the establishment of plate tectonics in the 1970s, calc-alkaline magmatism is considered as one of the most significant clues in identifying an active plate margin. Occurrence of magmatic arcs demonstrates the presence of lithospheric subduction, accretion and subsequent collision when those arcs crop out within continents. Plate tectonics during the Archean and Palaeoproterozoic is, however, still debated (e.g. Helmstaedt and Scott, 1992; Windley, 1992; Zhao et al., 2002). Recognition of Palaeoproterozoic horizontal mobility of lithospheric plates by combining structural, geochronological and geochemical studies is thus a key issue. This paper reports the discovery of a 2 Ga magmatic arc in north-eastern China and discusses its possible geodynamic setting in terms of subduction and collision. Geological setting Eastern Asia has resulted from the welding of several continental blocks such as Siberia, Mongolia, the North China Block (NCB) and the South China Block (SCB). East of the Tan-Lu fault, the Liaodong Peninsula belongs to the eastern part of the NCB, but geological information regarding this area is still rare. According to (LBGMR 1989), the Liaodong Peninsula consists of Archean and Palaeoproterozoic gneisses and migmatites overlain by Neoproterozoic to Triassic sedimentary rocks. Numerous granitic plutons of Cretaceous age intrude the lithological sequence. In the northern part of the Liaodong Peninsula, the SW–NEtrending Archean Anshan Complex consists of gneisses, granitoids and supracrustal rocks (Fig. 1). SHRIMP U⁄Pb zircon dating of gneisses and granitoids gave ages ranging from 3.8 to 2.5 Ga (Jahn and Ernst, 1990; Liu et al., 1992; Song et al., 1996). Palaeoproterozoic rocks of the Liaohe Group are widely exposed south of this Archean belt. Our work in this area leads us to distinguish two tectonic units, namely a Southern

Block and a mafic magmatic belt. In the Southern Block, three rock types are recognized, in ascending order: (i) a migmatized gneiss–amphibolite complex (Sun et al., 1993; Liu et al., 1997), (ii) a 3000 m-thick marble series with several Pb–Zn stratiform deposits and mafic magmatic intrusions, and (iii) a slate and quartzite series. The NE–SW-trending mafic magmatic belt that crops out between the Archean Anshan Block and the Palaeoproterozoic Southern Block consists of magmatic and sedimentary rocks. Magmatic rocks include cumulate pyroxenites, gabbros and more rarely diabase dikes. Although reported by earlier workers (e.g. Liu et al., 1989), pillow lavas have not been recognized during our field survey. Sedimentary rocks are red or pale grey siliceous shales, cherts and banded limestones with some sulphide pods. In the following, we argue that the mafic magmatic belt is a subductionrelated arc formed on the Southern Block and overthrust to the northwest above the Anshan Block. Structural aspects The mafic–ultramafic rocks form kilometre-scale klippen overthrust above metapelites and limestones. Metre- to hectometre-scale masses observed in the field are interpreted as tectonic blocks inserted within the sedimentary rocks. Near the basal sole thrust, the gabbros exhibit a mylonitic fabric, but most of the ductile deformation is concentrated in the sedimentary rocks within which planar and linear fabrics are conspicuously developed. To the north-west, the mafic magmatic belt has been thrust over the Anshan Complex along a low to moderate Fig. 1 Structural map of the northern part of Liaodong Peninsula. Unconformably covered by Neoproterozoic–Palaeozoic rocks, three lithotectonic domains are recognized, from north to south: (1) the Archean Anshan Block, (2) a magmatic belt and (3) a Southern Block. The bulk structure of the study area results from Palaeoproterozoic tectonics. Inset: the study area in the present geodynamic framework of East Asia. SE-dipping shear zone (Fig. 2). In both the underlying and the overlying units, flat-lying foliation consists of a N–S to NW–SE mineral and stretching lineation (Fig. 3). Shear criteria such as asymmetric pressure shadows or shear bands indicate a top-to-the- NW displacement under greenschist facies conditions. The central part of the mafic magmatic belt is characterized by high-angle dips, whereas to the south, the foliation dips north or north-east. There, the kinematic indicators show a top-to-the-SE shearing. The foliation is crenulated or folded with NE–SW-trending axes. Therefore, as a whole, the magmatic belt exhibits a double-verging, fan-like geometry (Fig. 2).

Owing to late NE–SW-trending vertical faults, the contact between the mafic magmatic belt and the southern Palaeoproterozoic Block is poorly exposed. However, the bulk geometry shows that the marble series and overlying slates dip below the mafic rocks. The consistency between the structural elements in the Anshan Block, the mafic magmatic belt and the Southern Block suggests that they are coeval. The structure of Liaodong Peninsula has been previously interpreted to be the result of extensional tectonics linked with the formation of a metamorphic core complex (Liu et al., 1997). However, in the study area, our field survey does not support such a structure. Another interpretation involving compression and thrusting is proposed below. Stratigraphically, the age of the tectonics is constrained only by the unconformable deposition of Neoproterozoic clastic rocks (i.e. Qingbaikou or Sinian groups, LBGMR, 1989).



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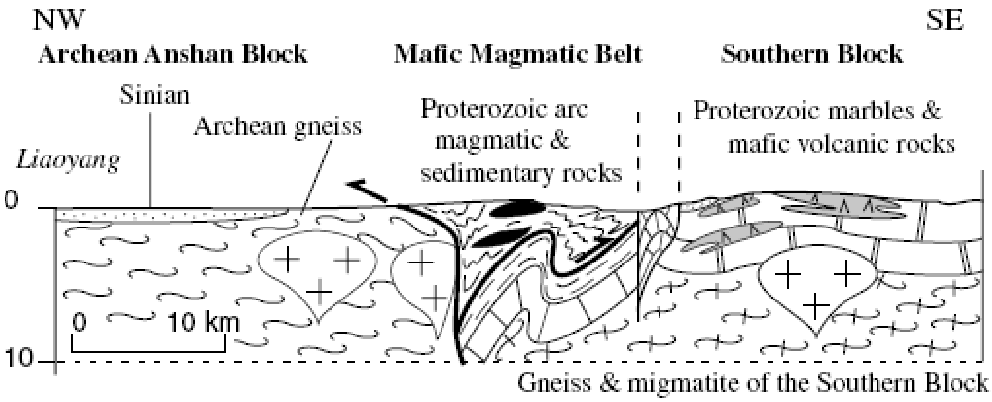

Fig. 2 Cross-section (location given in Fig. 1) showing the fan-shaped structure of the mafic magmatic belt overthrust upon the Archean Anshan Block and the southern Palaeoproterozoic Block, to the north and south, respectively.

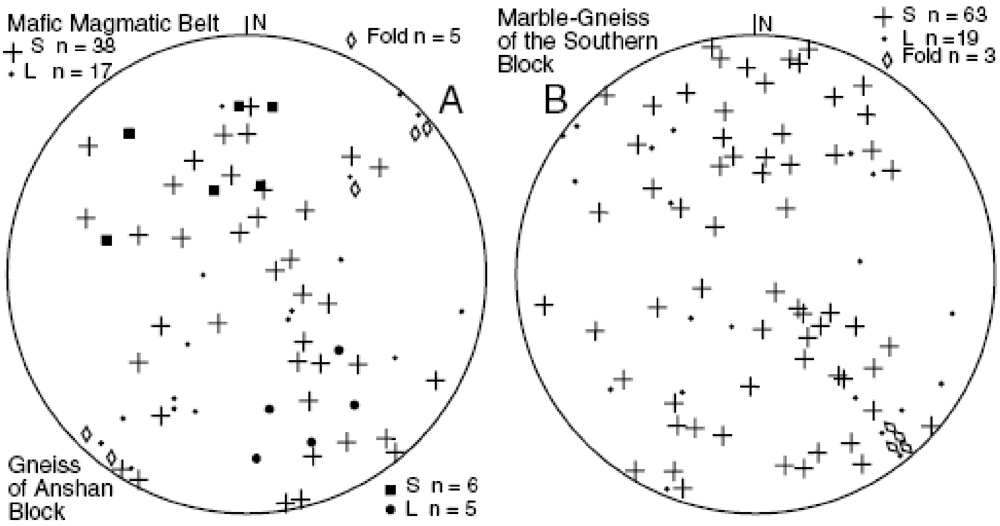

Fig. 3 Stereoplots of the planar and structural elements. A: Anshan Block and mafic magmatic belt; B: southern Block.

40Ar ⁄ 39Ar geochronology

During fieldwork, several samples of undeformed gabbro were collected along the mafic magmatic belt (see Fig. 1 for sample location). Three amphiboles have been separated from these samples for single grain laser probe 40Ar ⁄ 39Ar dating. The analytical device and procedures used in the 40Ar ⁄ 39Ar laboratory of the University of Montpellier are similar to that described in Monie´ et al. (1997). The age spectra are shown in Fig. 4.

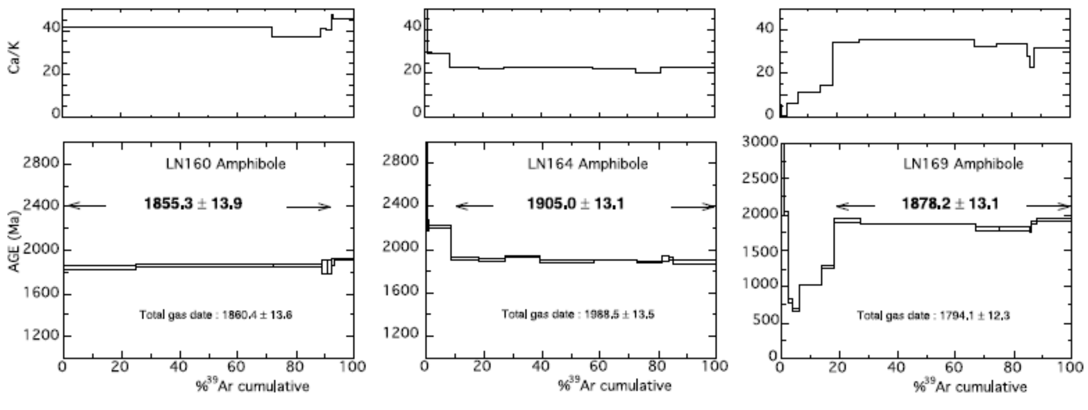

Fig. 4 40Ar ⁄ 39Ar age spectra and Ca ⁄ K diagrams of amphiboles from gabbros (located in Fig. 1) showing Palaeoproterozoic age

Owing to its small size and low potassium content, sample LN160 was degassed in essentially three heating increments. The apparent ages are concordant, and define a plateau date of 1855 ± 14 Ma with Ca ⁄ K ratios close to 40. These ages reach a maximum value of 1913 ± 8 Ma at the end of degassing, with a Ca ⁄ K ratio of about 45. Amphibole from sample LN164 exhibits a plateau age of 1905 ± 13 Ma for about 90% of the argon released, related to homogeneous Ca ⁄K ratios close to 22. The sample shows evidence of a weakly bound excess argon component released during the five first heating steps and related to higher Ca ⁄K ratios. Trapping of this excess argon could be related to the presence of minute Ca-rich inclusions in the amphibole, such as epidote (which was observed in thin sections). Sample LN169 produced the most complex age spectrum, characterized by excess argon at the beginning of degassing, then age depletion to a minimum of 686 ± 17 Ma, followed by an age increase and a series of apparent ages ranging from about 1800 to 1930 Ma. The Ca ⁄K spectrum reveals that the minimum ages are correlated with low Ca ⁄K ratios, probably reflecting the presence of secondary micaceous phases that crystallized during a still undated thermal overprint. The concave pattern of the age spectrum observed for the last 80% of 39Ar released probably results from this thermal overprint. For this portion of the spectrum, the Ca ⁄K ratios are relatively constant, with the exception of a small depletion that represents less than 2% of the gas released. Therefore, the best time constraint for cooling of the mafic magmatic belt is given by sample LN164, which yields a plateau age of 1905 ± 13 Ma, interpreted to date amphibole closure at a temperature in the range 500–600 °C (Dahl, 1996). The two other samples give maximum ages, respectively, of 1913 and 1930 Ma, which are consistent with this plateau age. However, sample LN169 clearly argues for the existence of a secondary thermal event (c. 1880 Ma) resulting in argon loss and trapping of micaceous inclusions. This event is probably coeval with the deformation of the enclosing sedimentary rocks.

Trace element geochemistry

Trace element analyses of one pyroxenite, three gabbros and one shale sampled in the mafic magmatic belt (locations given in Fig. 1) were performed by conventional nebulisation ICP-MS at the University of Montpellier II, following the procedure outlined in Ionov et al. (1992). Incompatible element patterns from the magmatic samples (Fig. 5) exhibit enrichment in LILE, such as Th and U, and moderate enrichment in LREE over marked depletions in HFS elements (Nb, Ta, Zr, Hf and Ti). This distinctive geochemical signature is typical of subduction-related magmas (Pearce and Peate, 1995) and is generally ascribed to immobility of HFS elements during slab-fluxing processes (e.g. McCulloch and Gamble, 1991). In addition, positive Pb spikes are present in all magmatic samples, which may result from its preferential extraction from the subducted oceanic crust and overlying sediments during dehydration processes (Miller et al., 1994). The enriched LREE patterns observed for samples LN164 and LN169 are similar to those of intraoceanic and continental arc rocks (e.g. Gribble et al., 1998; Shinjo et al., 1999). The slight LREE enrichment and less pronounced depletion in HFS elements observed in sample LN160 resemble back-arc basin rocks (Shinjo et al., 1999). Given the geochemical features of the analysed rocks that clearly point to a volcanic arc setting, the question then arises as to whether an intraoceanic or continental arc setting can be recognized. Figure 6 shows a plot of a non-conservative element (Th) vs. a conservative element (Nb), in which Yb is used as a denominator to minimize the effects of fractional crystallization (Pearce and Peate, 1995). Although all magmatic samples plot in the overlap region between the intra-oceanic and continental arc domains, the gabbros LN164 and LN169 and the pyroxenite LN157 plot close to the continental arc basalts from the Ryukyu arc, whereas the gabbroic sample LN160 plots close to the back-arc basin basalts of the Okinawa trough (Shinjo et al., 1999). This raises the possibility that the analysed samples developed in a continental arc setting. The shale sample mirrors the patterns of the arc rocks in terms of its negative Nb–Ta anomaly and positive Pb anomaly. Although LIL elements in the shale have similar or higher concentrations than in the arc rocks, the REE pattern is essentially shalelike, supporting a continental origin for the sediments. However, the REE content and flat HREE pattern (Yb ⁄SmCN ¼ 0.74) are similar to volcanic detritus, such as those from the Java fore arc (Plank and Langmuir, 1998), and suggest therefore that some of the sediments were also derived from the arc. This is consistent with the low Nb⁄Ta ratio of 13.5, intermediate between that of the arc-related rocks (LN 157, 160, 164 and 169) and the bulk continental crust (12–13 after Barth et al., 2000). The shale sample also exhibits a high Li content (c. 65 p.p.m.) and an associated pronounced positive Li anomaly, which is related to uptake of seawater Li into clay particles by substitution for Mg (Chan et al., 2002).

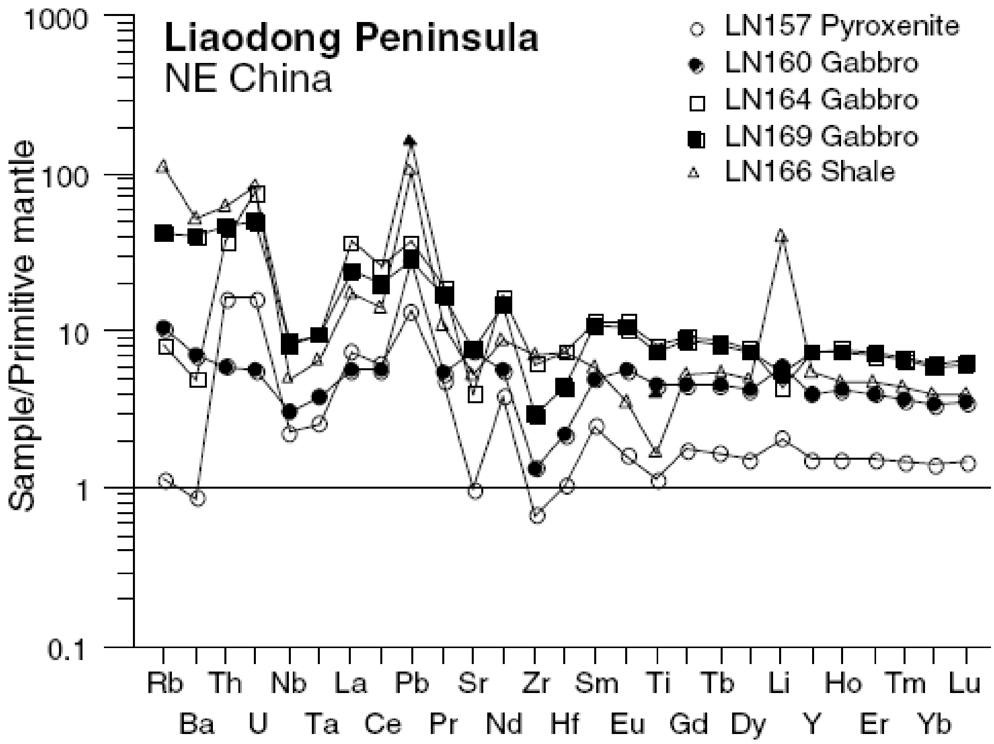

Fig. 5 Incompatible element abundances normalized to primitive mantle (McDonough and Sun, 1995) for rocks from the mafic magmatic belt (locations are given in Fig. 1).

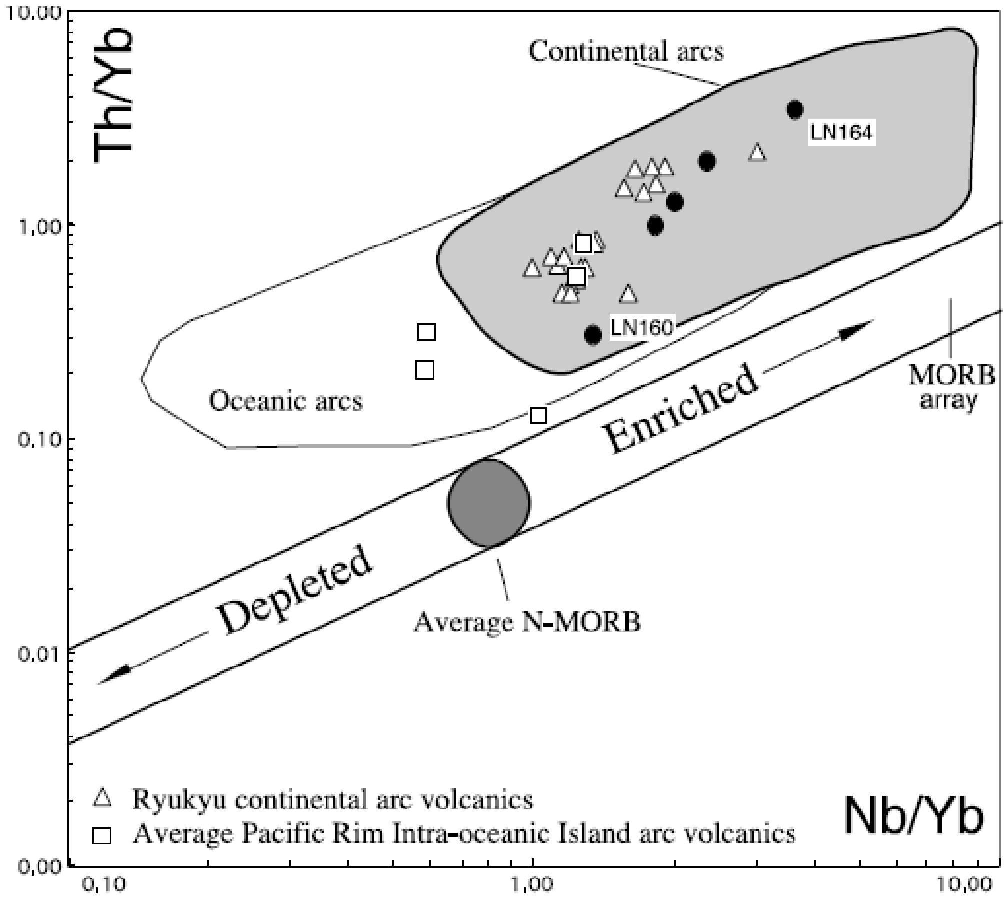

Fig. 6 Th/Yb vs. Nb/Yb diagram after Pearce and Peate (1995) showing the fields of continental and intra-oceanic island arcs. Open triangle: Ryukyu continental arc volcanics after Shinjo et al. (1999). Open square: average of Pacific rim intra-oceanic island-arc volcanics from the New Britain, Kermadec, Marianas, Aleutians and Vanuatu arcs, after McCulloch and Gamble (1991).

Discussion

The above data allow us to propose a new interpretation significantly different from previous models. The mafic rocks have been considered as emplaced in an intracontinental rift and subsequently deformed by extensional tectonics (Li et al., 1997; Liu et al., 1997). This view does not comply with the geochemistry of the studied rocks that imply that the mantle source was metasomatized by subduction-related fluids and with the sedimentary environment, both suggesting a marine active continental margin. Therefore, we consider the mafic magmatic belt as a Palaeoproterozoic magmatic arc formed by subduction. Because there are no petrological or geochemical differences between the mafic magmatic belt and the rocks that intrude the marble series in the Southern Block, these latter correspond to a more distal part of the same arc built upon a carbonate shelf. Geochemical analyses of amphibolites, located 50 km east of the study area and dated at around 1.9 Ga, also suggest an island-arc setting (Sun et al., 1993). Consequently, the subduction zone must dip below the southern Palaeoproterozoic Block. The collision between the Anshan and Southern Block resulted in NW-directed thrusting upon the Anshan Block. The top-to the- SE shearing corresponds to a back-thrust upon the southern Palaeoproterozoic Block. During the collision, the oldest rocks experienced thermal and structural reworking. The planar and linear fabrics observed in gneisses of the Archean Anshan Block developed during the 1.8–1.9 Ga deformation event (Song et al., 1996). In the Southern Block, the 2.1–1.9 Ga U/Pb, Sm/Nd and Rb/Sr ages of granitoids and gneisses are interpreted as reflecting a tectonothermal overprint upon older protoliths of c. 2.4–2.9 Ga age (Sun et al., 1993). Because closure temperature for argon in amphibole is in the range 500–600 °C (e.g. Dahl, 1996), it is likely that the 1.9 Ga age of the mafic magmatic belt does not relate directly to the time of subduction but to a subsequent cooling that could be much younger than subduction. However, the Palaeoproterozoic age (2100–1900 Ma, LBGMR, 1989) of the Liaohe Group suggests that arc magmatism took place just before the collision. These results show that the Palaeoproterozoic structure of the NCB might be more complex than depicted in currently proposed models (e.g. Zhao et al., 2002). In this new interpretation, the boundary between the Anshan Block and the Southern Block corresponds to a 2 Ga suture zone that might extend eastward in North Korea. Liaodong Peninsula appears as a continental block distinct from the main part of the NCB before Palaeoproterozoic times. Thus, the Palaeoproterozoic tectonic evolution of the Liaodong Peninsula provides a new example that in spite of a geotherm higher than at present, Archean cratons were rigid enough to experience horizontal mobility and deformation similar to present-day plate tectonics.

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